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INSERTION LOSS OF COMPOSITE SONAR DOME MATERIALS

J.P. Szabo & J.A. Hiltz

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Abstract

This document describes the results of research carried out at DREA in support of a DMSS tasking to investigate the acoustic properties of composite sonar dome materials. For thin panels (10 mm) at low frequencies (< 10 kHz), the composite materials studies here, as well as the double walled C5 stainless steel sonar window currently used on Canadian naval vessels, exhibited low insertion losses (< 1 dB). For thicker panels or higher frequencies, Spectra Fiber™ is a much better reinforcing fibre than either glass or carbon fibre, in terms of insertion loss. Spectra Fiber composite panels also had much better acoustic properties in the 10 – 50 kHz range than the C5 stainless steel sonar window (1 dB versus 10 dB at 40 kHz). There was no significant difference in the acoustic properties of panels fabricated with 4 harness satin or 8 harness satin fibre weaves. Panels made from epoxy or cyanate ester resin also had similar insertion losses. The effect of impact damage on the acoustic properties of Spectra and glass reinforced panels was not significant for 10 mm panels at frequencies < 10 kHz. However, there was a significant increase (up to 88 dB) in the insertion loss resulting from impact damage for thicker panels at higher frequencies. The use of elastomeric coatings n composite panels to mitigate impact damage is an approach that may lead to increases in the insertion loss, if air is entrapped between the coating panel.

Résumé

Le présent document décrit les résultats de recherches menées au CRDA dans le cadre d'une mission du DSN visant à étudier les propriétés acoustiques de matériaux composites de dôme sonar. Dans le cas de panneaux minces (10 mm) à basses fréquences (< 10 kHz), les matériaux composites étudiés ici, ainsi que la fenêtre sonar en acier inoxydable C5 à double paroi actuellement utilisée à bord des navires de guerre canadiens, avaient de faibles pertes d'insertion (< 1 dB). Dans le cas des panneaux plus épais ou des fréquences supérieures, la fibre Spectra[md] constitue une fibre de renforcement bien meilleure que les fibres de verre ou de carbone, pour ce qui est de la perte d'insertion. En outre, les panneaux composites en fibre Spectra avaient de bien meilleures propriétés acoustiques dans la gamme des 10 - 60 kHz que la fenêtre sonar en acier inoxydable C5 (1 dB contre 10 dB à 40 kHz). Il n'y avait pas de grande différence en ce qui concerne les propriétés acoustiques des panneaux à armure satin de quatre ou de huit. Les panneaux en résine d'époxy ou de cyanate avaient également des pertes d'insertion semblables. L'effet de dommages par choc sur les propriétés acoustiques des panneaux renforcés de fibre de verre et de fibre Spectre n'était pas important pour les panneaux de 10 mm aux fréquences inférieures à 10 kHz. Toutefois, il y avait une forte augmentation (jusqu'à 8 dB) de la perte d'insertion, due aux dommages par choc pour les panneaux plus épais aux fréquences supérieures. L'utilisation de revêtements élastomères sur les panneaux composites afin d'atténuer les dommages par choc peut accroître la perte d'insertion, si de l'air se trouve emprisonné entre le revêtement et le panneau.

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Insertion Loss of Composite Sonar Dome Materials

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Executive Summary

Background
Concerns over the high operations and maintenance cost associated with the stainless steel C5 sonar dome used on Canadian Naval vessels lead to a tasking from DMSS to investigate the acoustic and mechanical properties of composite materials that could be used to fabricate the dome. This report deals with the acoustic properties of the composite panels, and examines the effect of reinforcing fibre, weave, resin matrix, impact damage, and panel thickness on acoustic properties.

Principal Results
Spectra Fibre™ reinforced composites had very low insertion losses (<1 dB), even for relatively thick (30 mm) panels at high frequencies (40 kHz). Glass reinforced panels had good performance at frequencies < 10 kHz provided that the panels were thin (10 mm), but the insertion loss rose rapidly with frequency and thickness. The C5 stainless steel dome was found to have very high insertion losses (up to 10 dB) at high frequencies, but at frequencies < 10 kHz the insertion loss was < 1 dB. Impact damage was found to have a significant effect on the insertion loss of composite panels 20 mm or thicker at high frequencies.

Significance of Results
The current C5 dome is adequate in terms of acoustic performance at frequencies less than 10 kHz, but has very high insertion losses at higher frequencies. If the sonar system were to be used for higher frequency applications, then a sonar dome constructed from Spectra Fibre composite would provide excellent acoustic properties. Glass or carbon composites would still be superior to the current stainless steel dome at higher frequencies, but not as good as Spectra composites of similar thickness.

Future Work
Possible future work by DREA in this area includes (a) characterizing commercial off the shelf sonar window materials, such as RHO-COR, (b) developing improved sonar window materials, and (c) carrying out an analysis of the structural, hydrodynamic, and impact loads the dome may be subjected to, in order to determine the minimum thickness required for a given composite.

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1 Introduction

Hull mounted sonar equipment on naval vessels is usually covered with a dome, whose purpose is twofold: (a) to protect the sonar transducer and electronics from damage due to impacts and (b) to provide a smooth hydrodynamic surface to minimize flow induced noise associated with the sonar equipment. Unfortunately, introduction of the dome has unwanted side effects that reduce the effectiveness of the sonar equipment. First, the dome will introduce an acoustically opaque layer between the target and the sonar. The dome will attenuate and distort (change the frequency content of) the outgoing and incoming sonar signal, and this will result in a diminished capacity to detect, identify, and track enemy targets. Second, sonar self noise resulting from structurally induced vibrations in the dome, or hydrodynamic flow over the dome, will result in a reduced sonar performance. For these reasons, the design of the dome and the selection of appropriate materials are critically important to the optimal performance of the sonar system.

The C5 sonar dome currently installed on Canadian naval vessels is a double walled stainless steel design manufactured by Indal Technologies. In 1994, DREA was tasked by DMCS 3-3-6 to carry out a study of the acoustic and mechanical properties of stainless steel and composite sonar dome materials. The purpose of this document is to summarize the acoustic results obtained through research contracts and work carried out at DREA. The results of the mechanical experiments that were carried out at Esquimalt Defence Research Detachment, DREA are summarized in separate documents [1,2,3].

Preliminary work on the acoustic properties of composite and stainless steel sonar dome materials was carried out under contract at Guigné International Limited, Paradise, Newfoundland [4]. In that study, the insertion loss and its angular dependence were determined for 1 meter x 1 meter panels. In addition, attempts were made to determine the "self noise" characteristics of the panels. Subsequent research on the acoustic properties of the composite panels was carried out at DREA Dockyard Lab, and constitute the bulk of the work presented in this report. A study of the insertion loss of a full scale C5 dome was carried out in late 1998 at the DREA Barge in the Bedford Basin, and representative data from that trial is presented here.

2 Materials

Three separate sets of composite panels are reported on in this document.

2.1 Original Six Panels

The first set of panels included four high strength polyethylene (Spectra) fibre composites and two glass fibre composites, as summarized in Table 1. The prepregs used to fabricate the composite panels were made by Bryte Technologies Incorporated, Milpitas,

California. The prepregs incorporated one of three reinforcing fabrics impregnated with either a cyanate ester resin (BTCy-3) or an epoxy resin (BT250E). The three fabrics were: (a) Spectra 985PT, an eight harness satin weave fabric woven from 1000 Series plasma treated Spectra fibre; (b) Spectra 988PT, a four harness satin weave fabric woven from 1000 series plasma treated Spectra fibre; and (c) 7781Fg, an eight harness satin weave fabric woven from E-glass.

The composite panels were made by Advanced Composites Technology, Sparks, Nevada. The Spectra composites incorporated 27 plies of the prepregs (0°, 90°) and the glass composites 36 plies (0°, 90°). Fabrication involved vacuum bagging the assembled prepreg plies and applying a vacuum (25 inches Hg minimum) to consolidate the plies and remove excess resin. The composites were then cured in an autoclave under pressure (0.35 MPa). The cure cycle for the cyanate ester resin composites involved heating from room temperature to 120°C at a rate of 2°C/min, holding at 120°C ± 4°C for 5 hours, and then cooling at 5°C/min to below 70°C and removing the vacuum. The cure cycle for the epoxy resin was the same except that the hold time at 120°C was reduced to 2 hours. The panels were approximately 50% by weight resin content.

The original dimensions of the Spectra composites were 1005 mm X 1005 mm X 10 mm and the glass composites 1020 mm X 1080 mm X 10 mm. These large panels were cut into smaller panels, approximately 300 mm x 300 mm in size. These small panels were used to determine the effect of reinforcing fibre, fibre weave, and polymer matrix on the insertion loss [Section 3.5]. The panels were subjected to impact damage, to determine the effect of impacts on the acoustic properties of the panels [Section 3.9].

2.2 Thick Panels

The second set of composite panels were E-glass/epoxy and Spectra/epoxy composites of three different thicknesses: 10 mm, 20 mm, and 30 mm. A comparison of the acoustic data for these panels [Section 3.7] was used to determine the effect of thickness on insertion loss. Measurements were also carried out on these panels after impact damage [Section 3.9].

The composites were fabricated at Defence Research Establishment Atlantic, Dockyard Laboratory (Pacific) from prepregs made by Bryte Technologies Incorporated, Milpitas, California. The prepregs were made from either Spectra 985 or E-glass 7781 eight harness satin weave fabric impregnated with BT 250E-1 epoxy resin.

The 10 mm, 20 mm, and 30 mm E-glass/epoxy panels incorporated 40, 80, and 120 prepreg plies (0°, 90°) respectively with the exception of one of two 30 mm panels. Every second ply in this panel was orientated + and – 45° rather than 0°, 90°. The lay-up stacks were flipped up to down at mid-plane in the panels to avoid imbalances caused by the satin weave fabrics. The 10 mm, 20 mm, and 30 mm Spectra fibre/epoxy panels incorporated 28, 54, and 76 prepreg plies respectively. The cure of the 10 mm panels was the same as described above for the panels made at Advanced Composites Technology except that the autoclave pressure was 0.5 MPa. The cure for the thicker

samples was modified to prevent an exothermic overshoot. These panels were heated at a rate of 2C/min to between 105C and 110C and held for 15 minutes before ramping the temperature at 1C/min to 120C.

2.3 Elastomer Coated Panels

The third set of composite panels was prepared by coating 10 mm E-glass/epoxy panels with elastomeric coatings. The fabrication of the 10 mm composite panels is described in Section 2.2. Four of these panels were coated with various elastomeric materials, and subjected to impact damage. The acoustic properties of the undamaged and damaged panels that were treated with coatings were compared to a bare panel [Section 3.10]. The effect of these elastomeric coatings on the impact damage level is discussed in detail in Reference 2.

3 Acoustic Properties

3.1 Sonar Detection Range

The detection range of a sonar system depends on many factors, including sonar equipment parameters, the nature of the ocean acoustic environment, and the target strength. Consider for example, the active sonar equation pertaining to a noise limited environment [5]. When decibel units are used,

$$SL - 2TL_1 + TS = NL - DI + DT \tag{1}$$

In Equation (1), SL is the source level of the active sonar, TL is the transmission loss due to spreading and attenuation in the ocean environment, TS is the target strength, NL is the noise level due to ambient and self noise, DI is the receiving directivity index, and DT is the detection threshold. Equation 5 does not account for the effect of the sonar dome. Including the sonar dome adds an additional term, the insertion loss (IL):

$$SL - 2TL_2 - 2IL + TS = NL - DI + DT \tag{2}$$

If it is assumed that there is a cylindrical spreading loss, which occurs over medium and long ranges whenever sound is trapped in a channel in the sea [5], then the transmission loss follows an inverse first power law with distance R:

$$TL = 10 \log R \tag{3}$$

Combining equations 1-3 gives the relationship between the insertion loss (IL) of the sonar dome and the detection ranges with (R_2) and without the sonar dome (R_1):

$$
\begin{aligned}
TL_1 - TL_2 &= IL \\
10\log R_1 - 10\log R_2 &= IL \\
\frac{R_2}{R_1} &= 10^{\left[-\frac{IL}{10}\right]}
\end{aligned}
\tag{4}
$$

Equation 4 may be used to estimate the effect of the insertion loss of the sonar dome on the detection range of the sonar. As shown in Table 2, a sonar dome with an insertion loss of 1 dB will decrease the effective detection range by a factor 0.79, or 21% less than the case when no dome is present. An insertion loss of 10 dB will result in a 90% decrease in detection range.

3.2 Experimental Procedure

Experimental acoustic measurements were carried out in a small water filled tank using a parametric array projector [6] manufactured by Guigné International Limited, Paradise, Newfoundland. The theoretical and practical details of using parametric array sources for materials characterization may be found elsewhere [7,8]. The parametric source used a 1 MHz primary frequency modulated with a 10 or 20 kHz raised cosine bell envelope to obtain a secondary signal suitable for the 5 -50 kHz frequency range. A 0.75 mm thick stainless steel plate was inserted in the beam in order to filter out most of the primary signal. The 3 dB beamwidth of the truncated parametric array signal was approximately 7 degrees at 40 kHz. Samples were typically 300 mm x 300 mm in size and were oriented normal to the axis of the projector. Signal averaging was carried out on 50 or more pulses in order to increase the signal to noise ratio. The hydrophone was a polyvinylidene difluoride (PVDF) based polymer hydrophone manufactured by AMP sensors.

The insertion loss experiments involved two steps: (1) measuring the reference signal $P_r(t)$ with no panel present and (2) measuring the sample signal $P_s(t)$ with a panel inserted between the projector and hydrophone, as shown schematically in Figure 1. The Fast Fourier Transforms (FFTs) of these time domain signals were used to generate insertion loss information in the frequency (ω) domain:

$$
\begin{aligned}
P_r^*(\omega) &= FFT(P_r(t)) \\
P_s^*(\omega) &= FFT(P_s(t))
\end{aligned}
\tag{5}
$$

$$
IL = 20\log\left(\frac{P_s^*(\omega)}{P_r^*(\omega)}\right) \tag{6}
$$

This direct method for calculating the insertion loss spectrum will be called Method A. An additional method (Method B) was used which calculated what the idealized plane wave insertion loss spectrum should be, based on the measured panel thickness and density, and acoustic material properties that were extracted from the experimental data.

The following two sections describe in detail the equations which were used to interpret the experimental data and the results of experiments with calibration panels.

3.3 *Insertion Loss Model*

In Section 3.1, it was shown how the insertion loss of the dome may affect the detection range of an active sonar system. The insertion loss depends on the material properties of the sonar dome (density, sound speed, and attenuation coefficient), the thickness, and geometry of the dome. In addition, the insertion loss depends directly on the frequency, as well as indirectly if the material properties are frequency dependent. A simplified model of the sonar dome is employed here both to interpret experimental data, and to comment on the performance of various materials that may be employed in the fabrication of a sonar dome.

The one dimensional problem will be considered here, i.e. a plane wave that insonifies an infinite size panel at normal incidence. The effects of a sonar dome with a realistic 3-dimensional geometry may be modelled more accurately using finite or boundary element techniques. The insertion loss defined in terms of the simplified model is the decrease in acoustic pressure resulting from the insertion of a panel between the acoustic source and receiver, shown schematically in Figure 1, and expressed in decibels as

$$IL = 20\log\left(\frac{P_s}{P_r}\right) \tag{7}$$

where P_r is the reference pressure measured with no panel present, and P_s is the sample pressure measured with the panel inserted between the source and receiver. The theoretical framework developed by Brekhovskikh [9] is useful for modelling the response of single and multiple layers to plane wave insonification. It follows from equations presented by Mikesa and Behrens [10] that the insertion loss of a single homogeneous layer at normal incidence in water may be expressed in terms of the angular frequency ω, panel density (ρ), sound speed (c), and thickness (d), and water density (ρ_o) and sound speed (c_o):

$$IL = -20\log|T^*| \tag{8}$$

$$T^* = \left[\frac{4Ak^*}{(A+k^*)^2\exp(ik^*d)-(A-k^*)^2\exp(-ik^*d)}\right]\exp(ik_o d) \tag{9}$$

where

$$A = \rho\omega/(\rho_o c_o)$$
$$k^* = \omega/c - i\alpha$$
$$k_o = \omega/c_o$$

In the equations 8 and 9, $T^* = \frac{P_s^*}{P_r^*}$ is the complex transmission coefficient, $i = \sqrt{-1}$, and the asterix sign (*) indicates that the quantity is complex. For calculating the plane wave acoustic response of more than one layer, a general matrix based approach has been developed by Brekhovskikh [9] and Thomson [11,12]. The model can be used for any number of layers by setting up a matrix for each layer based on its properties, and then multiplying these matrices together to get a final matrix for all the layers, as described in detail in Reference 13. For the purposes of this work, it was assumed that the composite panels being characterized could be described in terms of a single layer. This assumption is a reasonable approximation at low frequencies, but as the wavelength approaches the thickness of the individual layers in the composite, one would expect that a single layer description would be inadequate. (For a 10 mm panel with 28 layers, this condition would exist for frequencies in the MHz range).

It was also assumed in these analyses that the panel sound speed and attenuation coefficient were independent of frequency over the frequency range studied (5 – 50 kHz). This is a reasonable approximation for fibre reinforced composites for which the attenuation coefficients are small and the sound speeds change slowly with frequency.

If we define $P_r(t)$ and $P_r^*(\omega)$ as the reference signal pressure in the time and frequency domains respectively, and $P_s(t)$ and $P_s^*(\omega)$ as the corresponding sample pressures, then $P_s(t)$ may be calculated from T^* and $P_r(t)$, using forward and inverse Fast Fourier Transforms (FFT and iFFT):

$$P_r^*(\omega) = FFT[P_r(t)] \tag{10}$$

$$P_s^*(\omega) = T^* \cdot P_r^*(\omega) \tag{11}$$

$$P_s(t) = iFFT[P_s^*(\omega)] \tag{12}$$

Equations 9 – 12 may be used to calculate the expected sample pressure waveform in the time domain, $P_s(t)$, if the reference signal $P_r(t)$ is known and the panel material properties are known. Alternatively, Equations 9 – 12 may be used to calculate the panel material properties c and α, given the time pressure signals $P_r(t)$ and $P_s(t)$, and the thickness and density of the panel. This latter calculation cannot be done directly, but must be done using iterative non-linear optimization, as described in detail in Reference 14. Once the panel material properties are known, Equations 8 and 9 may be used to calculate the insertion loss spectrum for panels of various thickness (Method B).

3.4 Calibration Panels

Figure 2 shows the time domain data for the case of a 25 mm thick HY80 steel panel. The expected time domain sample signal for this panel calculated using the plane wave insertion loss model (Equations 9-12) and known material properties agrees well with the experimental sample signal, as shown in Figure 2. The frequency content of these signals

computed by FFT are shown in Figure 3, and the insertion loss spectra computed using Methods A and B are shown in Figure 4, along with the insertion loss spectrum expected on the basis of the material properties derived from the literature. Method B agrees quite well with the expected curve in Figure 4. However the error in Method A is only low in the region defined by the bandwidth of the reference signal (6 – 21 kHz). This region, in turn is defined by the parametric array modulation frequency, which was F_m= 10 kHz for this one example, and 20 kHz for the rest of the data presented in this report. Although the frequency range of interest was mainly in the region < 10 kHz, a value of F_m = 20 kHz was used because the acoustic signal was much more intense overall, and much more stable than for F_m = 10 kHz. In retrospect, however, it might have been better to use the lower modulation frequency on the basis of the error for Method A.

Figures 5-7 show the insertion loss data for 3 mm aluminum, which has an insertion loss that is much lower than the 25 mm steel discussed above (3 dB versus 24 dB at 50 kHz). There is excellent agreement between the expected and measured sample time domain data (Figure 5), and between the expected insertion loss spectrum and the experimental insertion loss calculated by Method B (Figure 7). The effect of the modulation frequency on the error in Method A can be seen clearly in Figure 7. The frequency range indicated by the arrow corresponds to the peak width at half-height of $Pr(\omega)$, which in this case was 15 – 40 kHz for a parametric array modulation frequency of F_m = 20 kHz.

An example of the determination of insertion loss for panels with unknown acoustic properties is presented Figures 8 and 9 for a 10 mm thick glass/epoxy panel. Using a measured thickness of 10.0 mm and a density of 1840 kg/m^3, it was determined through an iterative optimization procedure (i.e. Method B) that the best fit acoustic properties for this panel were c = 2870 m/s and α = 2.0 Np/m. The best fit sample curve $P_s(t)$ using these material parameters agrees very well with the experimental one (Figure 8), and there is a high degree of confidence in the resulting insertion loss spectrum determined by Method B and shown in Figure 9.

The experiments with steel and aluminum calibration materials suggest that the insertion loss data derived using Method B are very accurate for an isotropic panel whose thickness and density may be accurately determined. The data also suggests that Method A can also be used, but one could expect errors up to 0.5 dB in the 10 kHz – 50 kHz frequency range, using this experimental apparatus and a parametric array modulation frequency of F_m = 20 kHz. For this reason, Method B was used to determine the insertion loss in most cases for the composite panels reported on here. However, in cases where there was a poor fit between the optimized and experimental time domain data, which was the case for impact damaged panels studied here, the insertion loss data was determined using Method A.

3.5 Spectra and Glass Composites

The insertion loss spectra of six different types of 10 mm composite panels are shown in Figure 10. At frequencies < 10 kHz, all the panels had insertion losses in the range 0 – 0.7 dB. At higher frequencies, the glass reinforced panels had significantly higher (in the

range of 3 dB higher at 50 kHz) insertion losses than the Spectra fibre reinforced panels. The effect of resin and weave is less clear from the data in Figure 10. A more statistically accurate picture of the effects of fibre, resin, and weave may be obtained by examining the data from three replicate trials on the same six panels. This data is shown in Tables 3 through 6. Using the data in these tables, Student t tests were carried out at two different frequencies, 10 kHz and 40 kHz, to test whether there were any significant effects of changing the fibre, resin, or weave. As can be seen in Tables 7 and 8, the Spectra Fiber panels had insertion losses that were lower than glass panels at both frequencies, as determined from the criterion $t > t_\alpha$ ($\alpha = 0.05$). However, the statistical analysis also shows that there was no significant effect on the insertion loss of changing the resin from cyanate ester to epoxy, or of changing the weave from 4H satin to 8H satin.

The replicate trial data were also used to examine more carefully the agreement between Method A and Method B for calculating insertion loss. Figure 11 shows a comparison of the two calculation methods for six panels and three trials, for a total of 18 observations per frequency. The results of a paired difference t test (Table 9) and Figure 11 both suggest that there was no significant difference between the two methods.

The measured density and the "best fit" acoustic properties for the six 10 mm composite panels are summarized in Table 10. The density of the Spectra based panels ($\rho \sim 1000$ kg/ m^3) are much closer to that of water ($\rho_o = 1000$ kg/ m^3) than the glass based panels ($\rho \sim 1800$ kg/m^3), and this accounts for much of the difference in acoustic behaviour for these two types of panels. The sound speeds of the Spectra reinforced panels are lower than the glass reinforced panels, and this contributes as well to the better performance of the Spectra panels.

3.6 Carbon Fibre Panel

While this study focused on Spectra and glass reinforced panels, a 14 mm carbon fibre/ epoxy panel was studied as well. The insertion loss of this panel is shown in Figure 12. The measured density for this panel was 1544 kg/m^3, and the acoustic sound speed and attenuation coefficient were found to be 2869 m/s and 1.42 Np/m respectively. The acoustic behaviour of the carbon/ epoxy panel is more similar to the glass/epoxy than the Spectra/epoxy, especially at higher frequencies, and this may attributed mainly to the high density of the carbon fibre panel.

3.7 Thick Panels

The effect of panel thickness on insertion loss was determined for glass/epoxy and Spectra/epoxy panels of thickness 10, 20 , and 30 mm. There was a large increase in the insertion loss with thickness for the glass/epoxy panels at frequencies up to 20 kHz (Figure 13). At higher frequencies, thickness resonances dominate the insertion loss spectra, with peaks at frequencies corresponding to multiples of $\lambda/4$ and troughs at frequencies corresponding to multiples of $\lambda/2$. The effect of thickness on the insertion loss of Spectra/epoxy panels is presented in Figure 14. The insertion loss of the

Spectra/epoxy panels is much less dependent on thickness than the glass/epoxy panels, as a comparison of Figure 13 and Figure 14 demonstrates.

The acoustic material properties of the glass/epoxy and Spectra/epoxy panels, derived from insertion loss data using Method B, may be used to predict the acoustic behaviour of panels of various thicknesses. One can use this information along with performance criteria for the panels to generate plots such as the ones shown in Figure 15 and Figure 16. If it is assumed that frequency window of interest is 0 – 10 kHz and the insertion loss must be less than 1.5 dB in that frequency range, then the maximum thickness that may be used is 41 mm for Spectra/epoxy and 17 mm for glass/epoxy. Similarly, a 0 – 30 kHz window and criterion IL < 1.0 dB would require panels to be no thicker than 15 mm for Spectra/epoxy and 4 mm for glass/epoxy.

The minimum thickness of the sonar dome will be determined by rigidity and strength requirements. Thus for a given material, there will be a range of acceptable thickness, determined by the strength and rigidity requirements on the low end, and the constraints imposed by acoustic performance at the high end.

3.8 Stainless Steel Dome

The C5 sonar dome currently being used on Canadian naval vessels, made by Indal Technologies Inc., is constructed from two stainless steel layers separated by a gap and held together by a network of frames. In operation, the space between the stainless steel skins is flooded with seawater. This geometry results in reasonably low insertion losses at frequencies less than 10 kHz, as shown in Figure 17 [4]. Above 10 kHz, the insertion loss is characterized by a series of resonance peaks and troughs resulting from the layered construction, and to a lesser extent, the internal steel ribbing. As can be seen from Figure 17, the insertion loss predicted for a steel / water / steel system with the same layer thicknesses as the dome agrees quite well with the experimental insertion loss.

An full scale stainless steel C5 dome was characterized at the DREA Barge in the Bedford Basin in 1998 [15]. Insertion loss measurements of this dome were carried out in the frequency range 10- 100 kHz, with an acoustic projector outside of the dome and a receiving hydrophone inside the dome. The measurements were made at three different receiving positions inside the dome, and with many different bearing angles. Representative spectra from two measurements are shown in Figure 18.

The data presented here suggest that the current C5 window would not be suitable for higher frequency (>10 kHz) sonar applications. The high insertion loss of the stainless steel window, as well as peaks and troughs in its insertion loss spectrum at higher frequencies, would make target detection and classification difficult. In contrast, sonar dome constructed from the composite materials studied here, and in particular the Spectra reinforced composites, would be expected to perform quite well at higher frequencies.

Figure 19 shows a comparison of the predicted insertion loss for the C5 dome (1.57 mm steel/54 mm water/1.57 mm steel) with a single layer of 1.57 mm steel.

3.9 Impacted Panels

The effect of impact damage on the acoustic properties of glass and Spectra composites is reported on in this section. The six 10 mm composite panels discussed in Section 3.5 were subjected to impacts up to 236 J at Defence Research Establishment Atlantic, Dockyard Laboratory (Pacific) [2]. The damage to the panels had several effects, such as tensile failure of glass fibres, plastic deformation of Sepctra fibres, and microcracking. In addition, ultrasonic imaging of the damaged areas clearly showed that the acoustic properties were affected in the MHz frequency range [16]. However, statistical analysis of the insertion loss data showed there was no significant effect of the impact damage on the measured insertion loss at 10 kHz or 40 kHz (Table 11).

The effect of impact damage on thick panels is less clear than for the 10 mm panels. The panels described in Section 3.7 were subjected to impact damage at Defence Research Establishment Atlantic, Dockyard Laboratory (Pacific) [3], and the acoustic properties of the panels were determined after impact. The impact energies for these panels are summarized in Table 12. Note that the impact energy imparted to these panels increased with thickness. As shown in Figures 20 and 21, none of the panels exhibited a significant increase in insertion loss at 10 kHz. However, the 20 and 30 mm glass/epoxy panels and the 30 mm Spectra/epoxy panels were greatly affected by impact damage at higher frequencies. In fact, there was up to 8 dB increase in the insertion loss for the 30 mm Spectra/epoxy panel at 40 kHz as a result of impact damage.

The actual effect of an impact on the overall acoustic performance of a sonar dome constructed from a composite material will depend on the area affected by the impact in relation to the total area that is used as a window for sonar signals. For these experiments, the insonified area was generally larger than the impact damaged area. Based on an estimated 10 degree beamwidth of the parametric array source at a modulation frequency Fm =20 kHz, the area insonified was approximately 14 cm in diameter. The area of the panels affected by the impact damage that could be assessed by visual means (ie strain whitening, cracking, plastic deformation) was approximately 8 cm in diameter.

3.10 Elastomer Coated Panels

Four 10 mm glass/epoxy panels were coated with various elastomeric coatings to determine whether the coatings would reduce damage due to impacts [2]. The effect of the elastomeric coatings on the insertion loss was also investigated. Figure 22 shows the measured insertion of 10 mm undamaged panels coated with 12.5 mm Isodamp C-1002 from EAR Corporation, 12.5 mm unfilled natural rubber, and polyurethane applied by Composites Atlantic in 5 and 10 mm thicknesses. Most of the coatings resulted in a significant (> 2 dB) increase in the insertion loss, even at 10 kHz. The 12 dB insertion loss at 10 kHz measured for the natural rubber coated panel was surprising considering natural rubber has acoustic properties similar to water. An acrylic based pressure sensitive adhesive was used to join the elastomer to the glass/epoxy substrate. It is possible that air was trapped between the coating and substrate, and this would contribute significantly to the high insertion losses. It can be shown through modelling that even

very thin layers of air can lead to very large insertion losses. For instance, a uniform 0.01 mm layer of air between the glass/epoxy panel and natural rubber coating is predicted to lead to an insertion loss of 11.5 dB, compared to 0.7 dB with no air gap present.

A large drop in the insertion loss of these coated panels was observed after the panels were subjected to impact damage, Figure 23. This decrease in insertion loss may be explained by an improved contact between the coatings and substrates as a result of impact loading. The panels were immersed in water for 24 hours prior to testing to ensure that no air bubbles would be present on the surface of the panel. An alternative explanation for the decrease in insertion loss is that air spaces in the interfacial region between coatings and substrates became filled with water prior to the second set of measurements.

The data suggests that the use of elastomeric coatings to mitigate impact damage of the sonar dome requires nearly perfect contact between the coating, adhesive, and substrate layers. Trapped air could be controlled (minimized) by applying appropriate loads during elastomer application, or by applying loads in a vacuum.

3.11 Self Noise Experiments

Experiments carried out at GIL under contract with DREA to examine the "self-noise" characteristics of various dome materials are reported in Reference 4. The intent of these experiments was to compare the acoustic radiation from mechanically excited composite panels with the radiation from the double walled stainless steel C5 dome material. It was anticipated that the composite materials, having higher material loss factors than stainless steel, would damp flexural vibrations in the panels to a greater extent than the steel panel, and therefore radiate less noise. The small scale experiments, carried out in a reverberant tank, were not conclusive and it was recommended that full scale tests should be carried out.

It may be that a composite sonar dome would have a greater effect on the performance of the sonar system through reduction in self noise than through lower insertion loss, especially at low frequency. This is supported by a previous study where it was reported that the C5 stainless steel window made a significant contribution to the sonar self noise [Reference 17, details classified]. Another approach to reducing sonar dome related self noise would be through the addition of free or constrained layer damping to the dome. Constrained layer damping is an integral aspect of the RHO-COR sonar dome material from BF Goodrich, which consists of a thick layer of rubber sandwiched between two glass reinforced plastic layers. Intrinsically damped composites are specifically designed to have high damping, and these types of materials should also be considered as potential dome materials.

3.12 Angle Dependence of IL

The dependence of the insertion loss on incident insonification angle for the 10 mm composite panels was reported on in Reference 4 and is summarized here. Measurements

of 1 meter x 1 meter panels were made at 0, 30, and 60 degrees to normal incidence. The difference in the normal (0 degrees) and non-normal insertion loss data was panel and frequency dependent. The largest changes were observed for the glass reinforced panels at high frequencies. For example, the 10 mm glass/epoxy panel insertion loss at 40 kHz and normal incidence is 3.5 dB, versus 0.5 dB for the same panel at 60 degrees incident angle. For Spectra reinforced panels, the insertion loss was generally in the range 0 – 1 dB for angles of incidence 0 – 60 degrees, and frequencies 5 – 40 kHz.

4 Summary and Recommendations

For optimum performance, the sonar dome should interfere minimally with the passage of acoustic radiation, i.e. it should be acoustically transparent. Even a 1 dB insertion loss in the sonar dome can have a significant impact on the detection range of the sonar target. The acoustic properties of Spectra and glass reinforced composites were investigated in this study using a parametric array source to determine the insertion loss of small panels. It was found that at frequencies < 10 kHz, 10 mm composite panels as well as the stainless steel sonar window had insertion losses less than 1 dB. In terms of acoustic properties, there was no significant difference between panels incorporating the 8H and 4H satin weaves, or between the cyanate ester and epoxy resins. The reinforcing fibre had a much greater effect, with Spectra panels having lower insertion losses than glass panels under most conditions. This difference was small but statistically significant for thin (10 mm) panels at low frequencies (< 10 kHz), but became much larger for thicker panels at higher frequencies.

The stainless steel C5 dome performs well at frequencies < 10 kHz, but at higher frequencies the insertion loss rises rapidly. Both small scale and full scale data would suggest that if higher frequency capabilities of the sonar system are desired, then there would be definite advantages in using Spectra reinforced composite material for the dome. The insertion loss of 30 mm thick Spectra/epoxy panels is ~ 1 dB at 40 kHz, which is much lower than the 10 dB insertion loss for the stainless steel window at the same frequency. Calculations indicate that the detection range at 40 kHz of an active sonar system incorporating a Spectra fibre composite dome would be 8 times longer than the same system with a double walled stainless steel dome (see Table 2 for 1 dB and 10 dB insertion losses). Since higher frequencies may be important for certain types of detection and tracking, this information should be considered in any upgrade to the present hull mounted sonar systems on Canadian frigates.

The acoustic properties of Spectra and glass reinforced panels damaged by impacts were not greatly affected at low frequencies (< 10 kHz). However, at higher frequencies there was a significant increase in the insertion loss for 20 and 30 mm panels as a result of impact damage. The use of elastomeric coatings on the composite panels to mitigate impact damage is an approach that should be used with caution, since even small amounts of entrapped air can lead to large increases in the insertion loss.

5 Acknowledgements

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6 Tables

Table 1. First set of composite panels, manufactured with satin weave fibres and Bryte Technology resins. Thicknesses were nominally 10 mm.

Panel ID	Fibre	Matrix	Weave	Abbreviated Description
985PT/ BTCY-3	Spectra	cyanate ester	8 harness satin	Spectra/cyanate 8H
988PT/BTCY-3	Spectra	cyanate ester	4 harness satin	Spectra/cyanate 4H
985PT/ BT250E	Spectra	epoxy	8 harness satin	Spectra/epoxy 8H
988PT/ BT250E	Spectra	epoxy	4 harness satin	Spectra/epoxy 4H
7781 Fg/ BT250E	E-glass	epoxy	8 harness satin	Glass/epoxy 8H
7781 Fg/ BTCY-3	E-glass	cyanate ester	8 harness satin	Glass/cyanate 8H

Table 2. Effect of insertion loss of sonar dome on the effective range of an active sonar system in a noise limited environment and with cylindrical spreading loss.

Insertion Loss (dB)	Range (arbitrary units)
0	1
1	0.79
2	0.63
5	0.32
10	0.10

Table 3. Insertion loss at 10 kHz of 10 mm composite panels determined by Method A

	Insertion Loss at 10 kHz (dB)			Average	Standard Deviation
	Trial 1	Trial 2	Trial 3		
Spectra/cyanate 8H	-0.02	0.06	0.64	0.23	0.36
Spectra/cyanate 4H	0.24	0.12	0.38	0.25	0.13
Spectra/epoxy 8H	0.62	0.17	0.50	0.43	0.23
Spectra/epoxy 4H	0.34	0.12	0.40	0.28	0.15
Glass/epoxy 8H	0.56	0.62	0.53	0.57	0.05
Glass/cyanate 8H	0.17	0.69	0.69	0.52	0.30

Table 4. Insertion loss at 10 kHz of 10 mm composite panels determined by Method B

	Insertion Loss at 10 kHz (dB)			Average	Standard Deviation
	Trial 1	Trial 2	Trial 3		
Spectra/cyanate 8H	0.08	0.16	0.56	0.27	0.26
Spectra/cyanate 4H	0.19	0.09	0.18	0.15	0.06
Spectra/epoxy 8H	0.36	0.16	0.24	0.25	0.10
Spectra/epoxy 4H	0.19	0.11	0.28	0.19	0.08
Glass/epoxy 8H	0.41	0.43	0.43	0.42	0.01
Glass/cyanate 8H	0.64	0.70	0.70	0.68	0.04

Table 5. Insertion loss at 40 kHz of 10 mm composite panels determined by Method A

	Insertion Loss at 40 kHz (dB)			Average	Standard Deviation
	Trial 1	Trial 2	Trial 3		
Spectra/cyanate 8H	0.59	1.00	1.50	1.03	0.46
Spectra/cyanate 4H	0.79	0.67	0.96	0.81	0.15
Spectra/epoxy 8H	1.18	1.05	1.17	1.13	0.07
Spectra/epoxy 4H	0.65	0.92	1.08	0.89	0.22
Glass/epoxy 8H	3.28	3.55	3.35	3.39	0.14
Glass/cyanate 8H	3.53	3.74	3.25	3.51	0.25

Table 6. Insertion loss at 40 kHz of 10 mm composite panels determined by Method B

	Insertion Loss at 40 kHz (dB)			Average	Standard Deviation
	Trial 1	Trial 2	Trial 3		
Spectra/cyanate 8H	0.69	0.76	1.31	0.92	0.34
Spectra/cyanate 4H	0.74	0.74	0.86	0.78	0.07
Spectra/epoxy 8H	1.16	0.86	1.02	1.01	0.15
Spectra/epoxy 4H	0.76	0.75	0.97	0.83	0.13
Glass/epoxy 8H	3.45	3.67	3.65	3.59	0.12
Glass/cyanate 8H	3.46	3.62	3.56	3.55	0.08

Table 7. Two tailed t-test results for insertion loss (dB) at 10 kHz (Method B)

	Glass	Spectra	Cyanate	Epoxy	8H	4H
Mean	0.55	0.22	0.37	0.29	0.26	0.172
Variance	0.02	0.02	0.08	0.02	0.03	0.004
Observations	6	12	9	9	6	6
Pooled Variance	0.02		0.05		0.02	
Hypothesized Mean Difference	0		0		0	
df	16		16		10	
t Statastic	4.89		0.78		1.18	
t Critical two-tail	2.12		2.12		2.23	
Significant Difference	Yes		No		No	

Table 8. Two tailed t-test results for insertion loss (dB) at 40 kHz (Method B)

	Glass	Spectra	Epoxy	Cyanate	8H	4H
Mean	3.57	0.89	1.81	1.75	0.97	0.81
Variance	0.01	0.04	1.80	1.86	0.06	0.01
Observations	6	12	9	9	6	6
Pooled Variance	0.03		1.83		0.03	
Hypothesized Mean Difference	0		0		0	
df	16		16		10	
t Statastic	31.78		0.09		1.52	
t Critical two-tail	2.12		2.12		2.23	
Significant Difference	Yes		No		No	

Table 9. Paired difference t-test results for insertion loss (dB) of 10 mm composites. Comparison of Method A and Method B.

	10 kHz		40 kHz	
	Method A	Method B	Method A	Method B
Mean	0.38	0.33	1.79	1.78
Variance	0.06	0.04	1.51	1.72
Observations	18	18	18	18
Pearson Correlation	0.721		0.993	
Hypothesized Mean Difference	0		0	
df	17		17	
t Statastic	1.31		0.33	
t Critical two-tail	2.11		2.11	
Significant Difference	No		No	

Table 10. Measured density and acoustic properties for six 10 mm composite panels.

Panel	Density (kg/m^3)	c (m /s)	alpha (Np / m)
Spectra/cyanate 8H	977	2413	4.0
Spectra/cyanate 4H	1003	2345	1.6
Spectra/epoxy 8H	1041	2333	3.4
Spectra/epoxy 4H	1027	2254	2.3
Glass/epoxy 8H	1849	2621	0.0
Glass/cyanate 8H	1632	2758	11.4

Table 11. Paired difference t-test results for insertion loss (dB) of 10 mm composites. Comparison of undamaged and damaged panels (Method A).

	10 kHz		40 kHz	
	Not Damaged	Damaged	Not Damaged	Damaged
Mean	0.38	0.42	1.79	1.84
Variance	0.06	0.07	1.51	1.13
Observations	18	18	18	18
Pearson Correlation	0.26		0.91	
Hypothesized Mean Difference	0		0	
df	17		17	
t Statastic	0.59		0.44	
t Critical two-tail	2.11		2.11	
Significant Difference	No		No	

Table 12. Impact energy (kJ) imparted to glass/ epoxy and Spectra/ epoxy panels of different thicknesses (see Section 2.2) [3].

Panel Thickness (mm)	Glass/ Epoxy	Spectra/ Epoxy
10	0.42	0.31
20	1.15	0.86
30	1.58	1.18

7 Figures

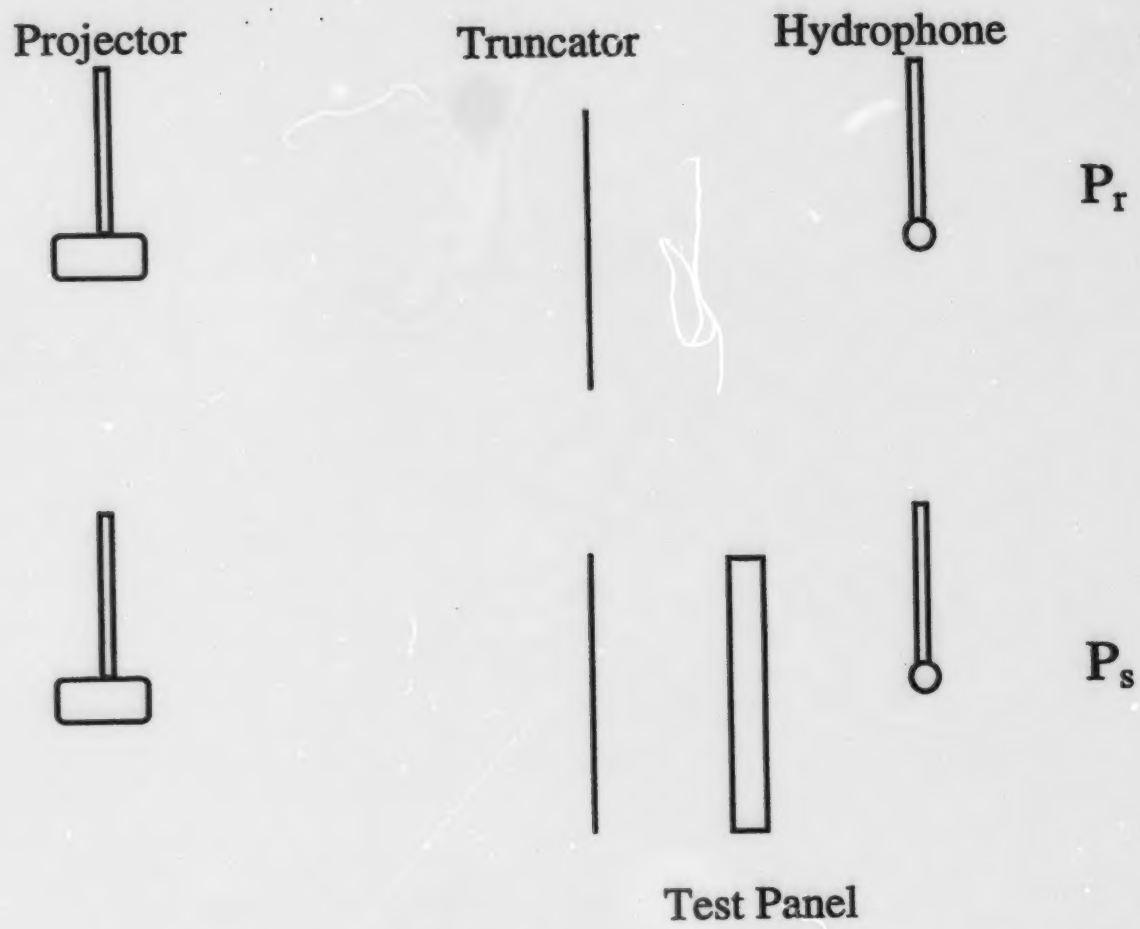

Figure 1. Schematic diagram showing test apparatus and two steps involved in the insertion loss experiment. A reference signal (Pr) is first measured with no panel present, and then a sample signal (Ps) is measured with the panel inserted between the acoustic projector and hydrophone.

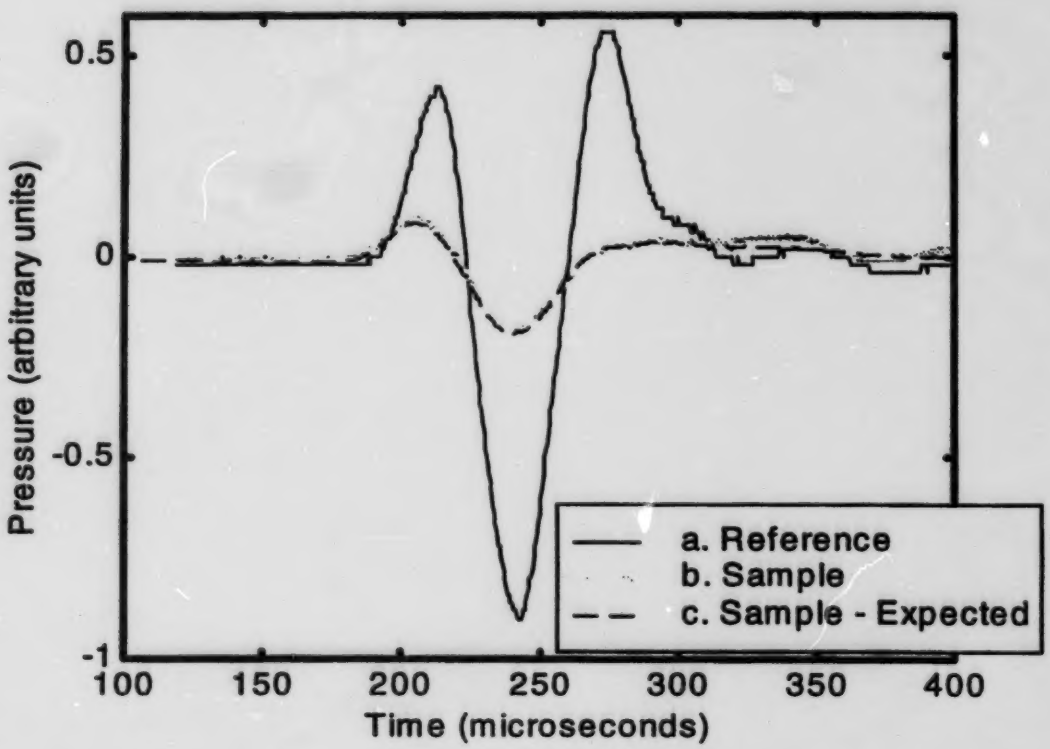

Figure 2. Time domain insertion loss data for 25 mm thick steel (Fm = 10 kHz). (a) Reference pulse with no sample present. (b) Response with sample inserted between source and hydrophone. (C) Calculated response using known material properties: c = 5960 m/s , $\alpha = 0$, and $\rho = 7870$ kg/m^3 [18,19] .

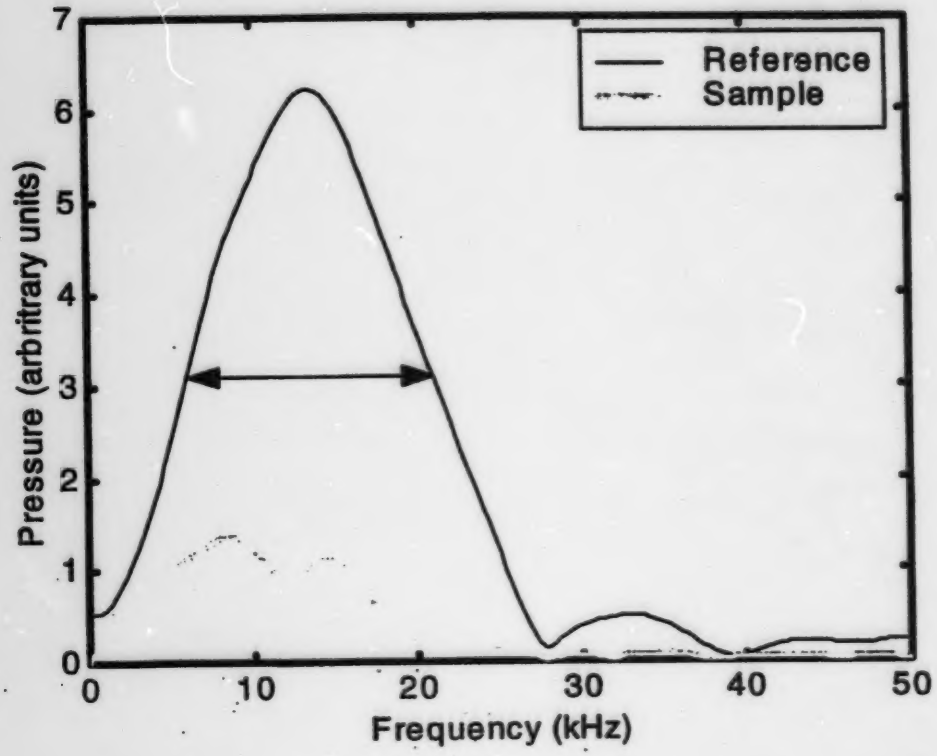

Figure 3. FFT of time signals in Figure 2. The arrow shows the frequency range over which the reference signal is greater than ½ its peak value.

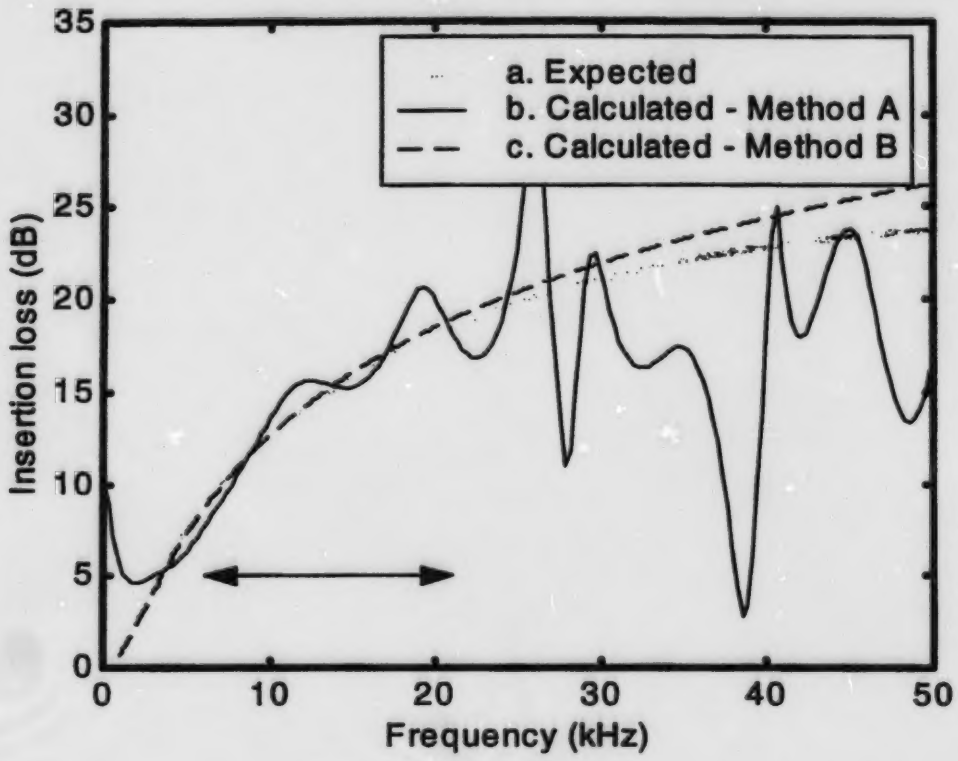

Figure 4. Insertion Loss spectra of 25 mm HY80 steel (a) calculated using known material values: c = 5960 m/s , α = 0, and ρ = 7870 kg/m3 , (b) calculated from experimental data by taking the ratio of the two curves in Figure 3 (Method A), and (c) calculated from experimental data using known thickness and density, and optimized c and α (Method B). The arrow shows the frequency range over which the reference signal is greater than ½ its peak value (Fm = 10 kHz).

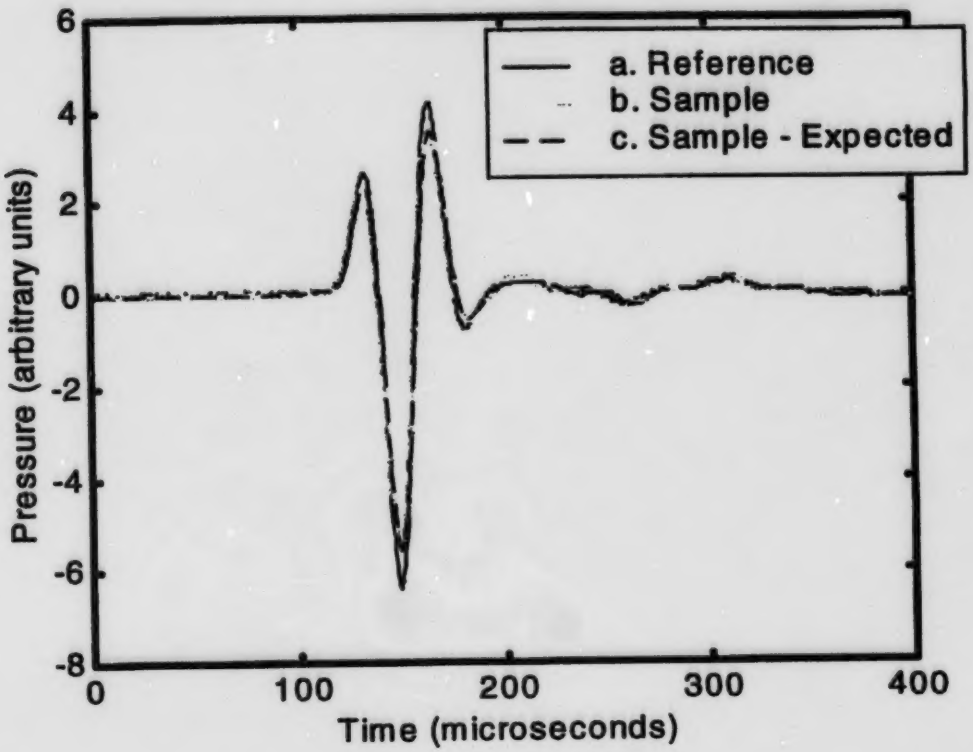

Figure 5. Time domain insertion loss data for 3.38 mm aluminum (Fm = 20 kHz). (a) Reference pulse with no sample present. (b) Response with sample inserted between source and hydrophone. (c) Calculated response using known material properties: c = 6374 m/s , α = 0.4 Np/m, and ρ = 2702 kg/m^3 [18, 20].

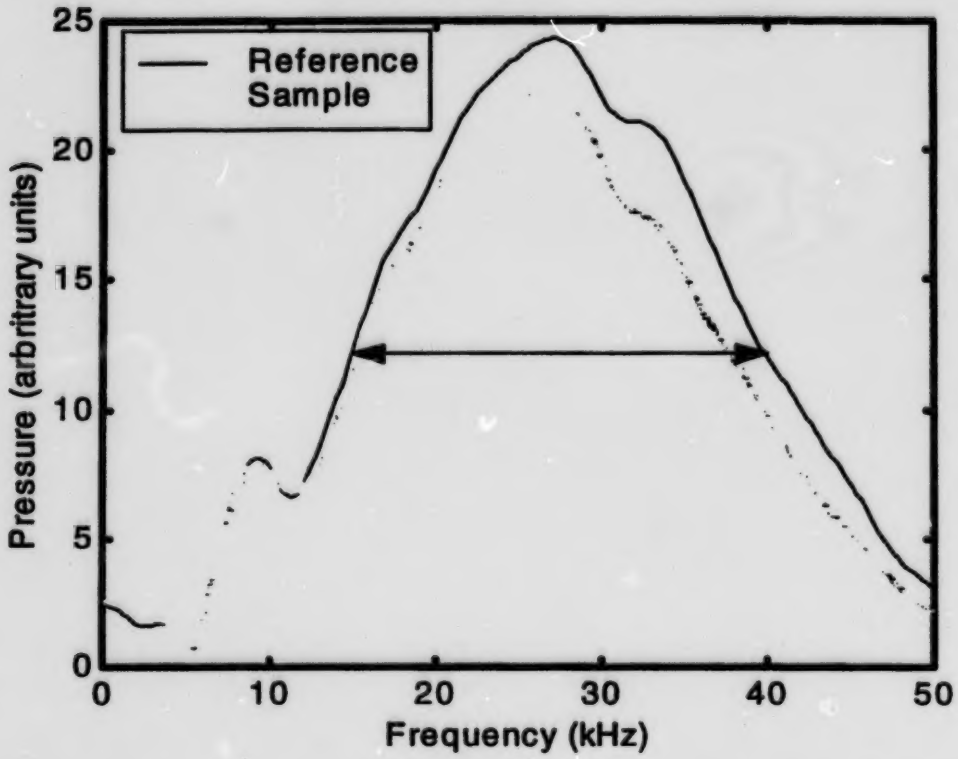

Figure 6. FFT of time signals in Figure 5. The arrow shows the frequency range over which the reference signal is greater than ½ its peak value.

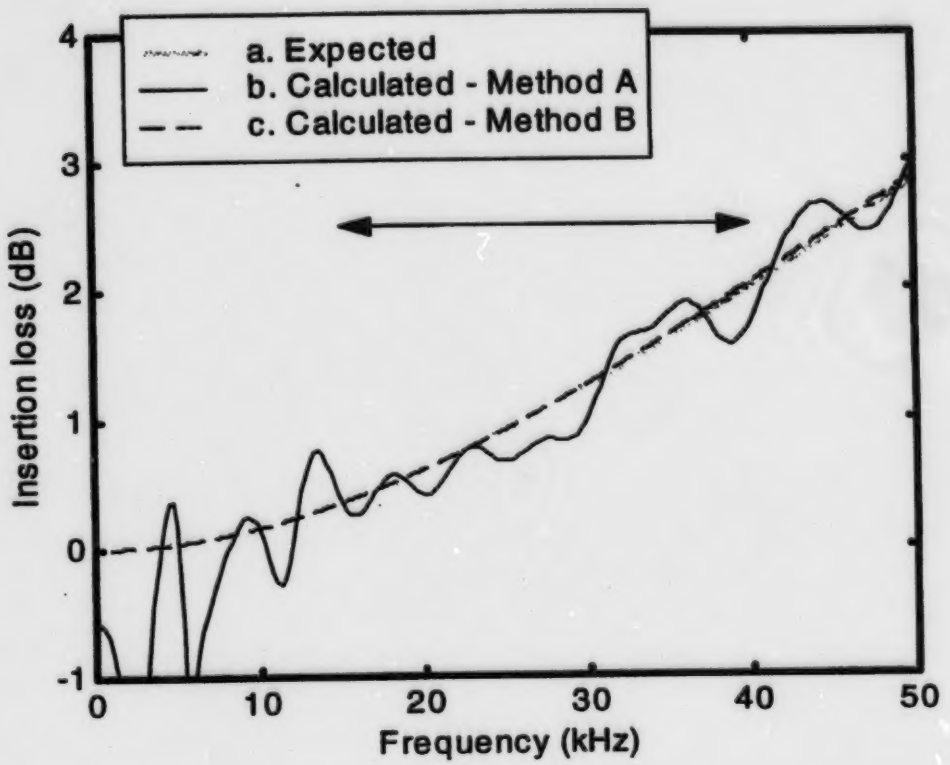

Figure 7. Insertion Loss spectra of 3.38 mm aluminum (a) calculated using known material values: $c = 6374$ m/s , $\alpha = 0.4$ Np/m, and $\rho = 2702$ kg/m^3 , (b) calculated from experimental data by taking the ratio of the two curves in Figure 6 (Method A), and (c) calculated from experimental data using known thickness and density, and optimized c and α (Method B). The arrow shows the frequency range over which the reference signal is greater than ½ its peak value (Fm = 20 kHz).

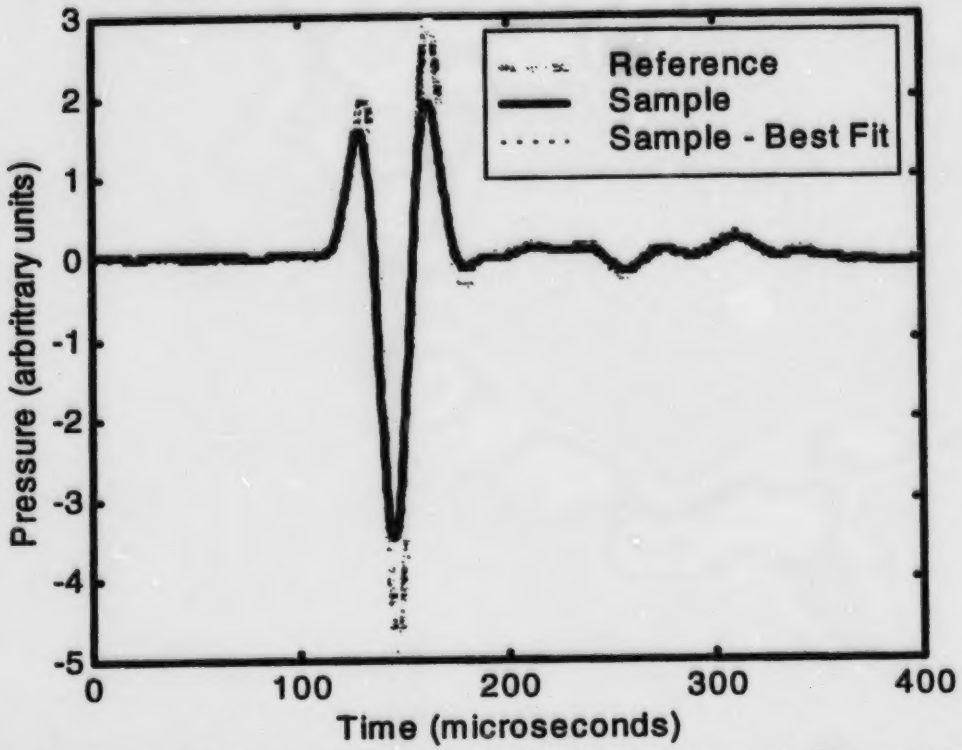

Figure 8. Example of time domain data for 10 mm glass/epoxy panel. The experimental reference and sample curves are shown, as well as the calculated sample curve using known thickness and density, and optimized c and α (Method B).

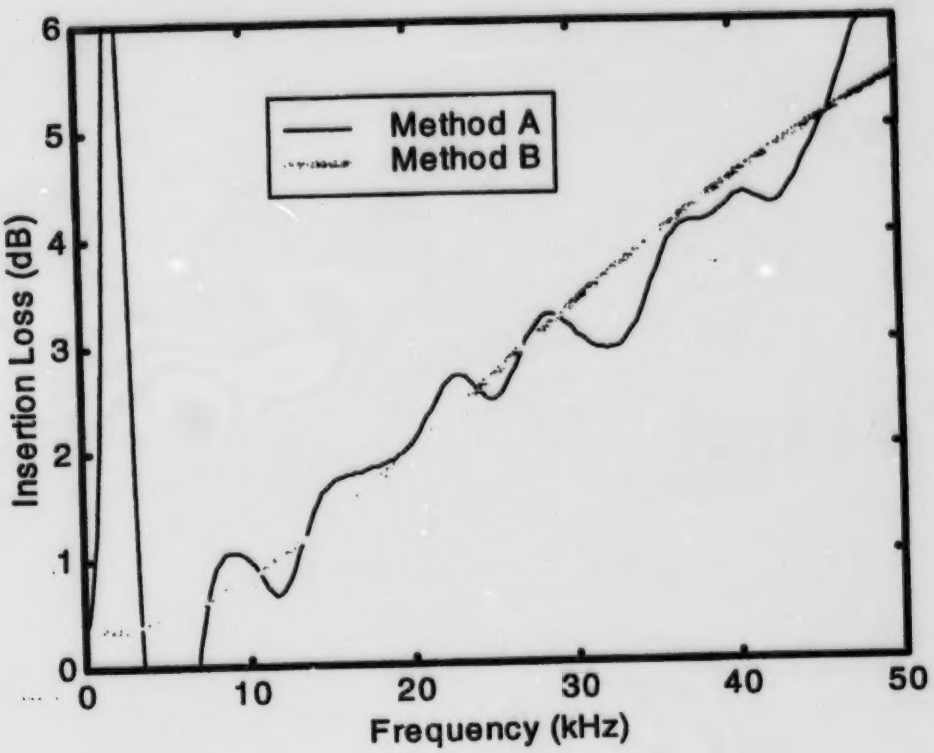

Figure 9. Insertion loss spectra for 10 mm glass/epoxy panel in Figure 8 determined using Method A and Method B. Note that the modulation frequency of the parametric array source was 20 kHz.

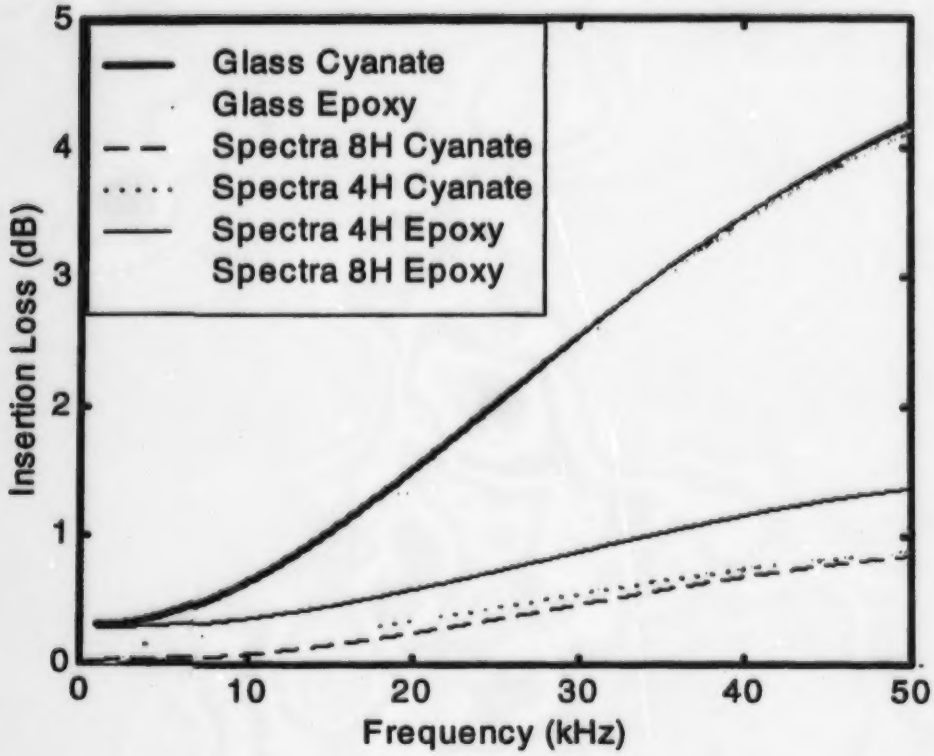

Figure 10. Insertion loss of undamaged 10 mm thick composite panels calculated using known thickness and density, and optimized c and α (Method B).

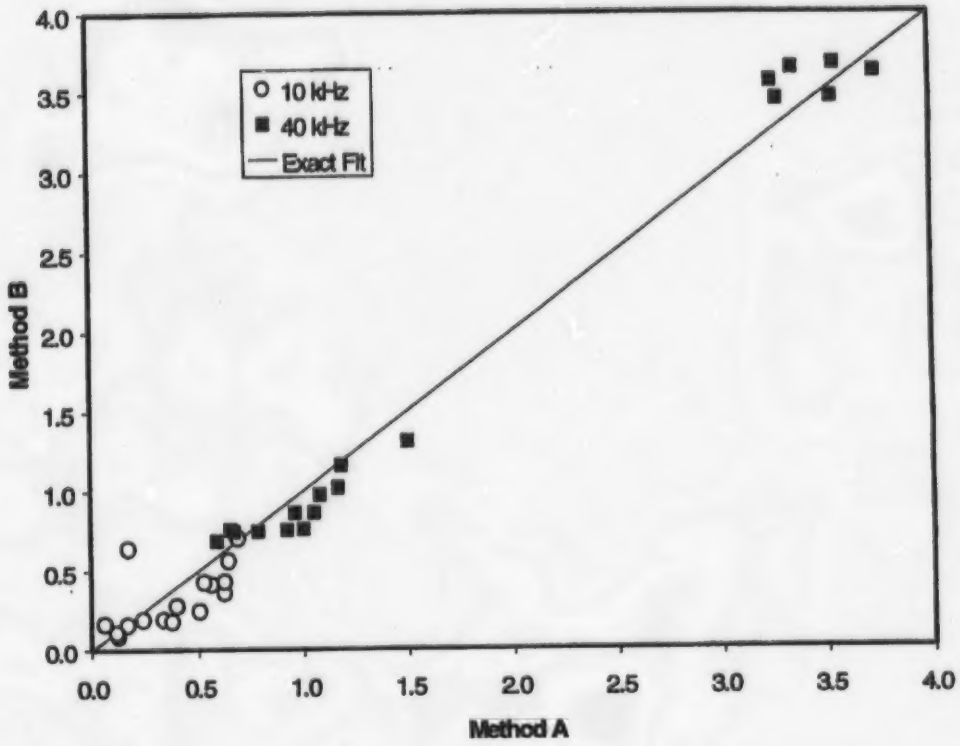

Figure 11. Comparison of insertion loss calculated using Method A and Method B for six panels and three trials, for a total of 18 observations per frequency.

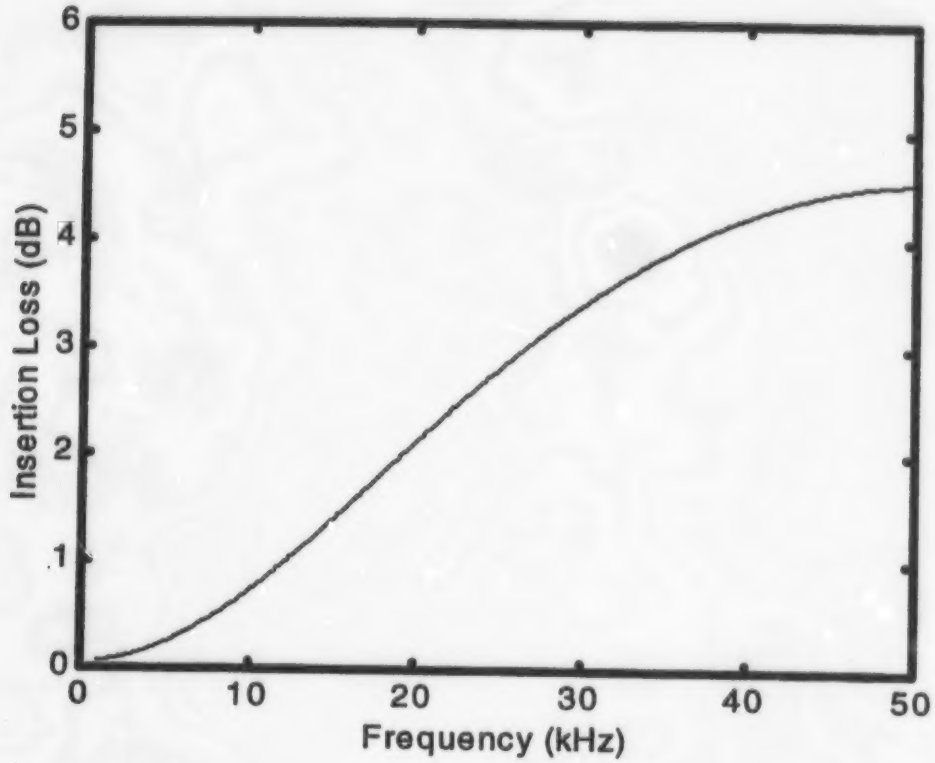

Figure 12. Insertion loss spectrum of 14 mm carbon fibre/ epoxy panel (Method B).

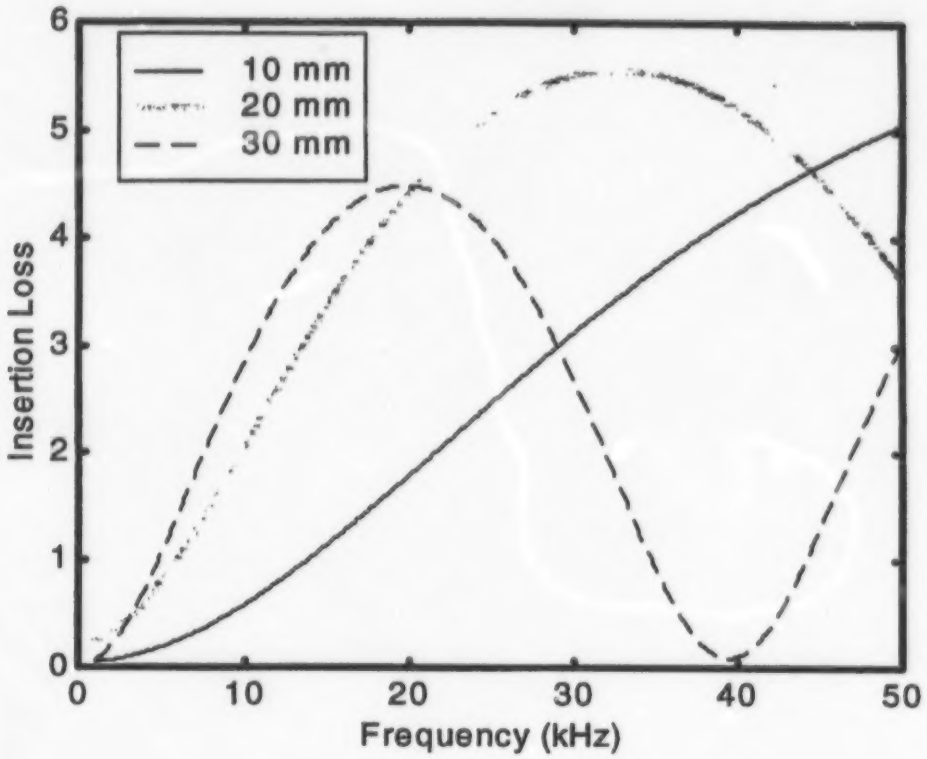

Figure 13. Insertion loss of glass/epoxy panels for three different thicknesses calculated using known thickness and density, and optimized c and α (Method B).

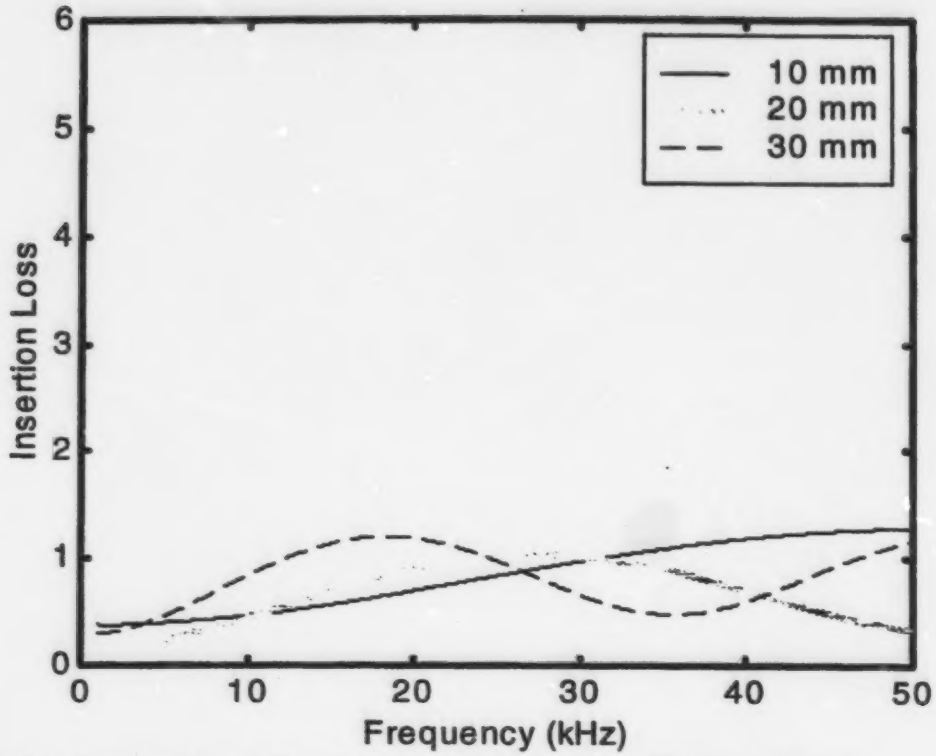

Figure 14. Insertion loss of Spectra/epoxy panels for three different thicknesses calculated using known thickness and density, and optimized c and α (Method B).

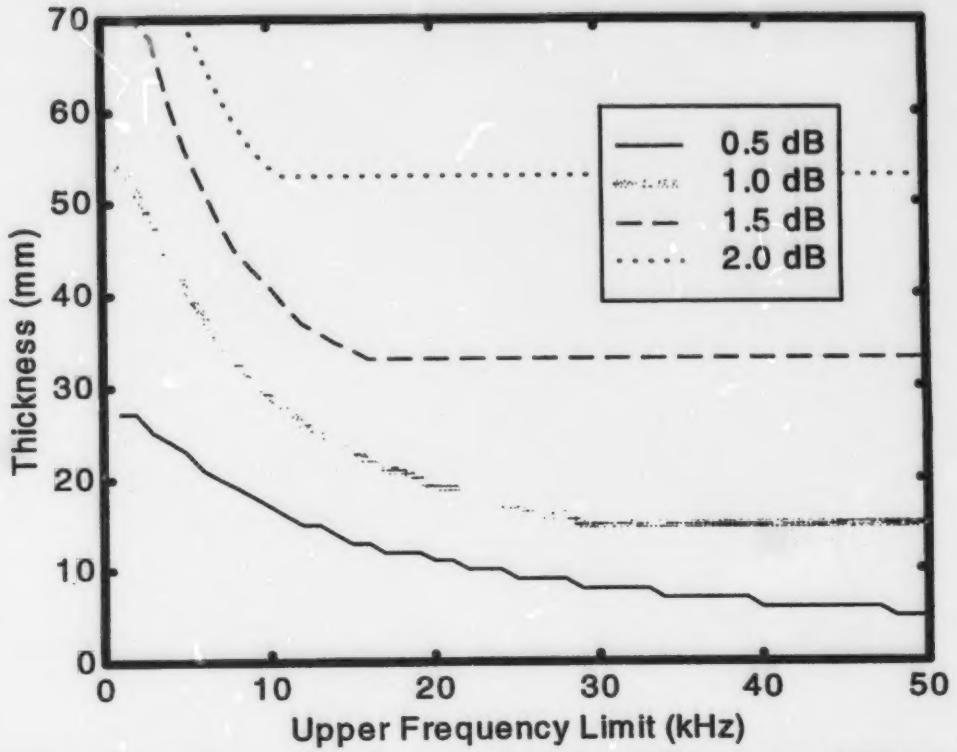

Figure 15. Upper frequency limit for the condition IL < x dB for panels of different thickness, calculated using the following material properties for Spectra/epoxy composites: $\rho = 1009$ kg/ m^3, $c = 2190$ m/s, $\alpha = 3.07$ Np/ m.

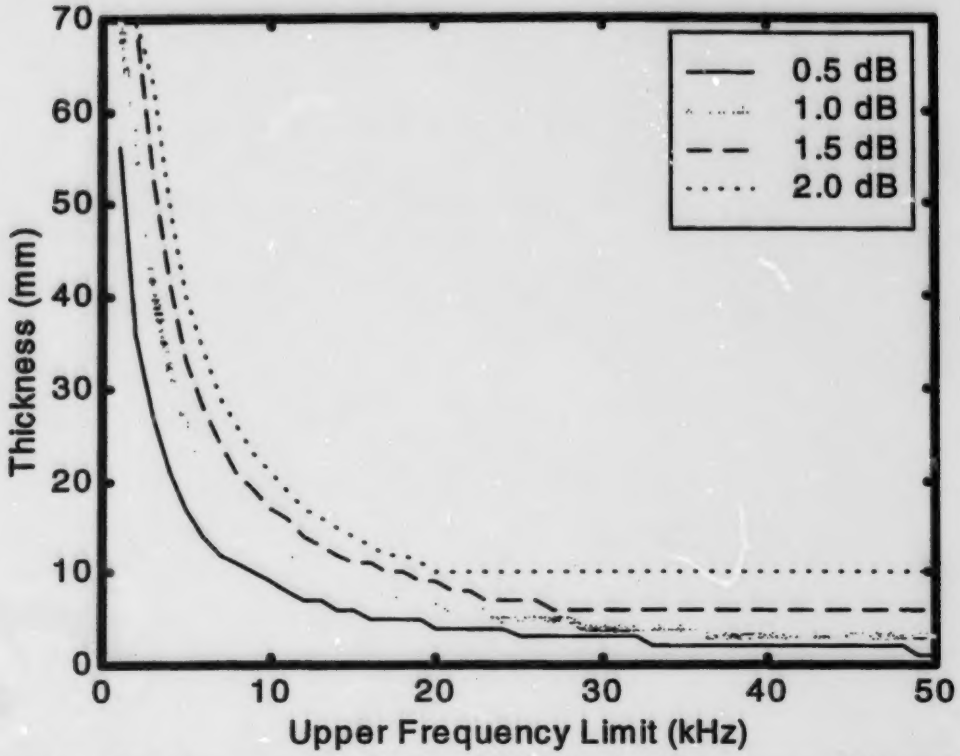

Figure 16. Upper frequency limit for the condition IL < x dB for panels of different thickness, calculated using the following material properties for glass/epoxy composites: $\rho = 1840$ kg/ m^3, $c = 2720$ m/s, $\alpha = 2.07$ Np/ m.

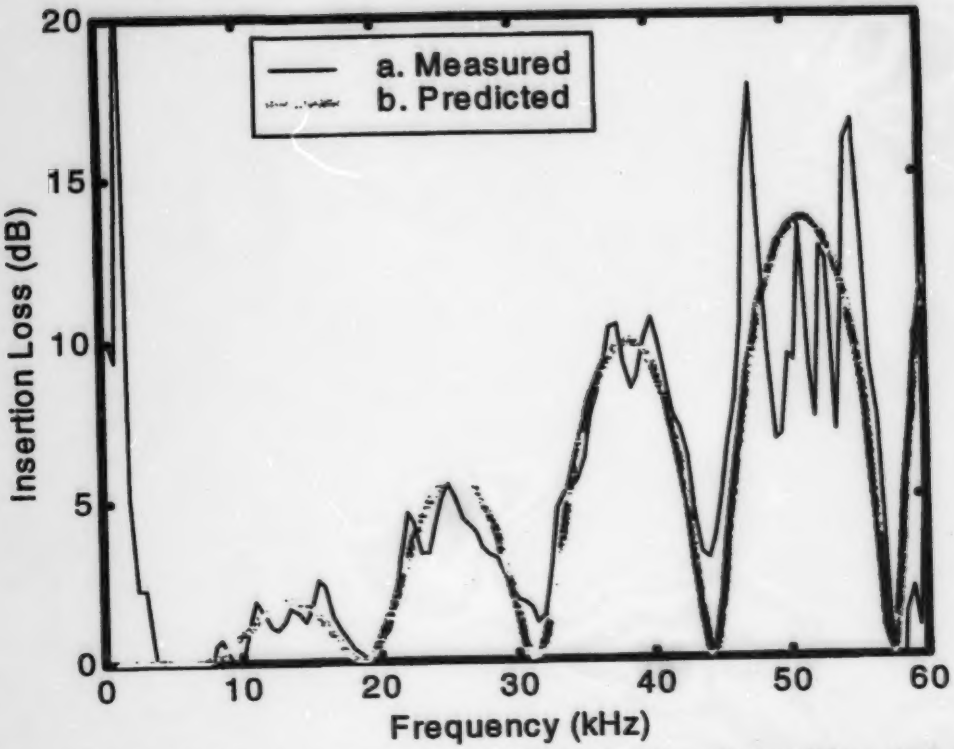

Figure 17. Normal incidence insertion loss of C5 double walled stainless steel dome. (a) Experimental data from 1 meter x 1 meter section [Reference 4] . (b) Predicted insertion loss for 1.57 mm steel/54 mm water/1.57 mm steel calculated using methods described in Reference 13.

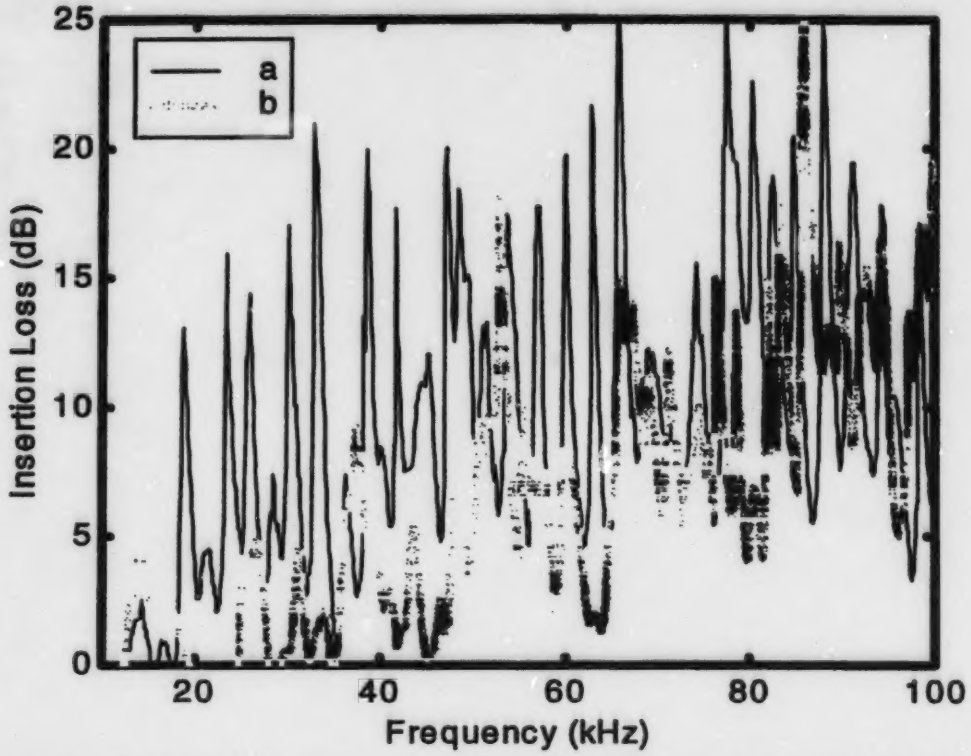

Figure 18. Insertion loss spectra of a full scale stainless steel C5 sonar dome from experiments at the DREA Barge. (a) Receiving hydrophone located in lower part of dome. Projector located 15 degrees down from hydrophone position, and at a bearing of 20 degrees from the main axis of the dome. (b) Receiving hydrophone located in upper part of dome. Projector at same depth as hydrophone, and at a bearing of 20 degrees from the main axis of the dome. Reproduced with permission from Ian Cobb, FMF Cape Scott, Halifax, Nova Scotia.

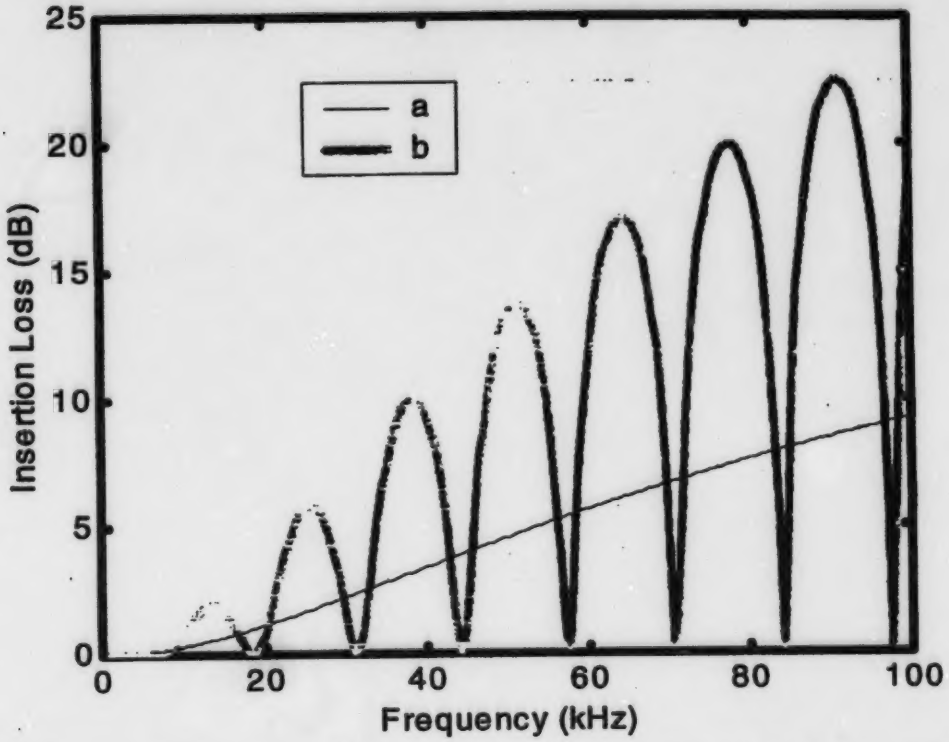

Figure 19. Predicted normal incidence insertion loss for (a) 1.57 mm steel, and (b) 1.57 mm steel/54 mm water/1.57 mm steel calculated using methods described in Reference 13.

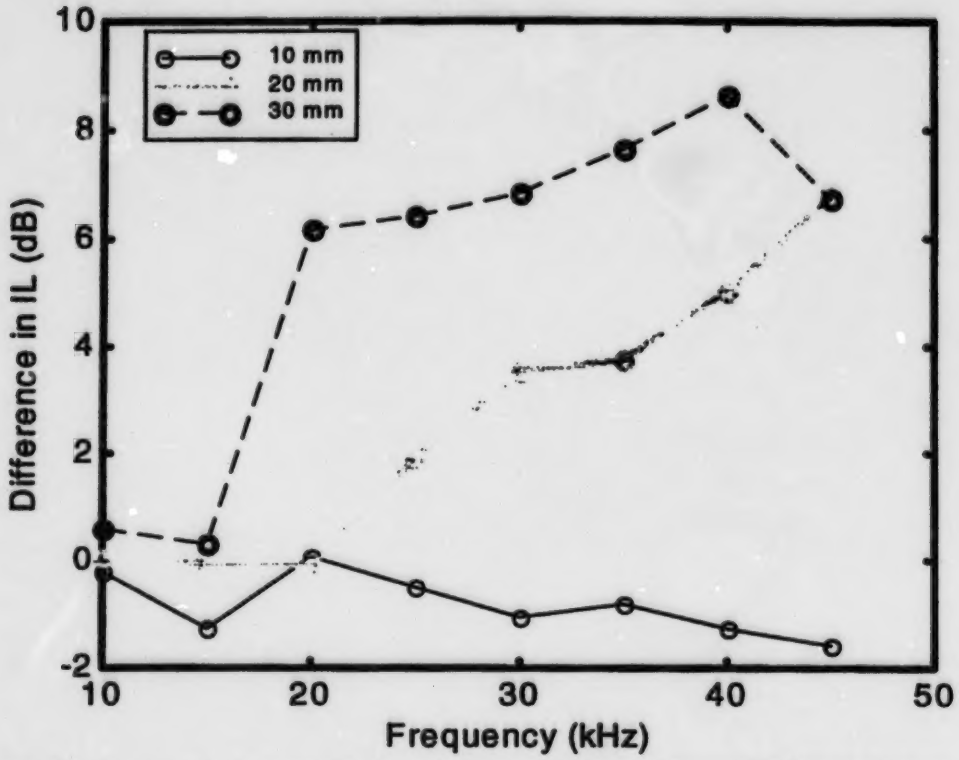

Figure 20. Increase in insertion loss as a result of impact damage for Spectra/epoxy panels of different thicknesses. Insertion loss was computed using Method A.

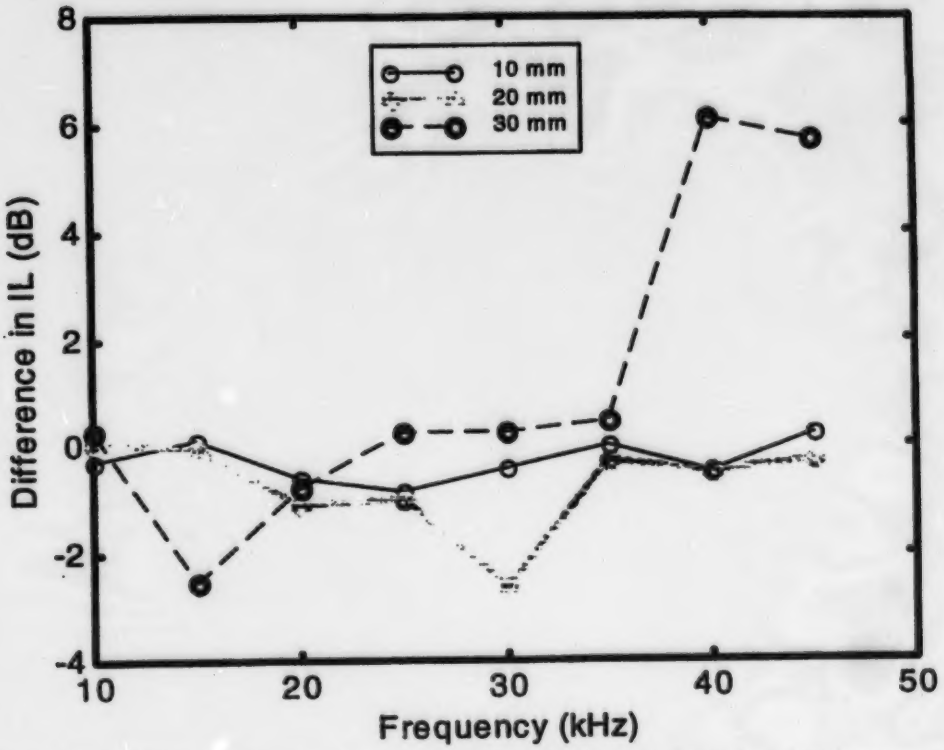

Figure 21. Increase in insertion loss as a result of impact damage for glass/epoxy panels of different thicknesses. Insertion loss was computed using Method A.

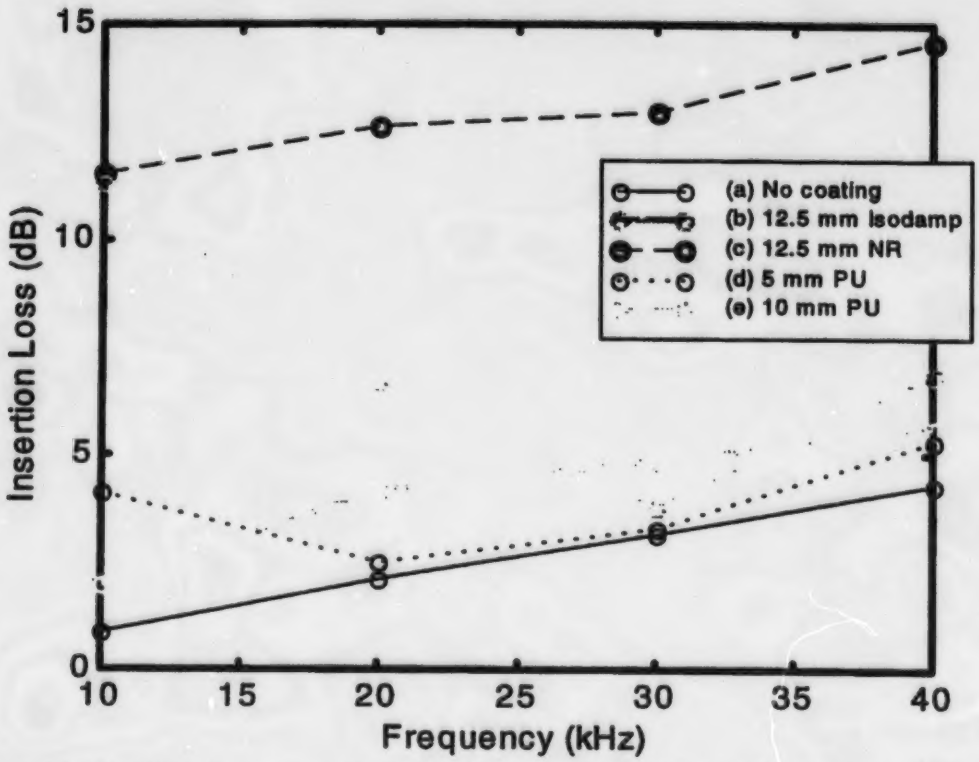

Figure 22. Insertion loss versus frequency for undamaged 10 mm glass/epoxy panels with various coatings: (a) uncoated panel, (b) 12.5 mm EAR Isodamp C-1002, (c) 12.5 mm natural rubber, (d) 5 mm polyurethane, (e) 10 mm polyurethane. Insertion loss was computed using Method A.

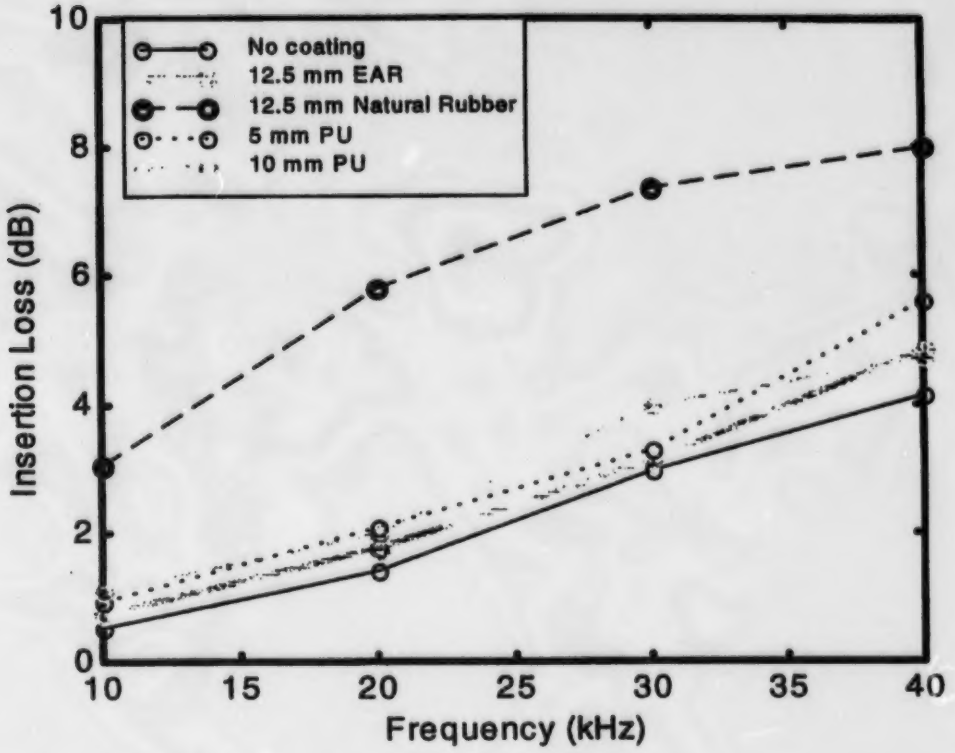

Figure 23. Insertion loss versus frequency for 10 mm glass/epoxy panels with various coatings after impact damage: (a) uncoated panel, (b) 12.5 mm EAR Isodamp C-1002, (c) 12.5 mm natural rubber, (d) 5 mm polyurethane, (e) 10 mm polyurethane. Insertion loss was computed using Method A.

8 References

1. A. J. Russell and D. S. Liesch, "Mechanical Behaviour of Candidate Sonar Dome Materials Part 1: Static Tests" DREA Technical Memorandum 1999-027 (1999).

2. A. J. Russell and D. S. Liesch, "Mechanical Behaviour of Candidate Sonar Dome Materials Part 2: Fatigue Tests", DREA Technical Memorandum, in review.

3. A. J. Russell and D. S. Liesch, "Mechanical Behaviour of Candidate Sonar Dome Materials Part 3: Impact Tests", DREA Technical Memorandum, in review.

4. Quanshun Liu and Jacques Y. Guigné, "Acoustic Properties of Sonar Dome Materials", DREA Contractor Report 96/420 (1996).

5. R.J. Urick, Principles of Underwater Sound, 3rd edition, McGraw Hill Book Company, 1983.

6. P.J. Westervelt, "Parametric End-Fire Array", J. Acoust. Soc. Am., **32**, 934A (1960).

7. V.F. Humphrey, "The Measurement of Acoustic Properties of Specimens of Limited Size by Use of a Parametric Source, J. Sound and Vibration, **98**, 67 (1985).

8. V. F. Humphrey and H. O. Berktay, "The Transmission Coefficient of a Panel Measured with a Parametric Source," Journal of Sound and Vibration, **101**, pp. 85-106 (1985).

9. L.M. Brekhovskikh, Waves in Layered Media, Trans. Robert T. Beyer, Second Edition, Academic Press, New York (1980).

10. E.E. Mikesa and J.A. Behrens, "Evaluation of Transducer Window Materials", J. Acoust. Soc. Am., **59**, 1294 (1976).

11. W.T. Thomson, "The Equivalent Circuit for the Transmission of Elastic Waves Through a Plate at Oblique Incidence", J. Appl. Physics, **21**, 1215 (1950).

12. W.T. Thomson, "Transmission of Elastic Waves Through a Stratified Solid Medium", J. Appl. Physics, **21**, 89 (1950).

13. S.M. Whelan, V.H. Chin, and J. Guigné, "A Multilayered Model for Simulation of Acoustical Parameters", DREA Contract Report CR/93/408.

14. E.L. Taylor and J.P. Szabo, "From Mechanics to Acoustics: Modelling Polymer Properties", DREA Technical Memorandum 95/211 (1995).

15. Personal communication, Ian Cobb, FMF Cape Scott, Halifax, February 1999.

16. J.P. Szabo, J.A. Hiltz, and A.J. Russell, "Impact Properties of Composite Sonar Dome Materials", Abstracts and Summaries of the 3rd (7th) CF/CRAD Meeting on Naval Applications of Materials Technology, DREA SR/97/002, Halifax, April 1997.

17. D. Martin, "AN/ SQS-505 Sonar Dome Noise Reduction Project. Supplementary Report: Sonar Performance Figure Investigation", DND Contract W8477-6-BB11/01-SV, April 1990.

18. G.W. Kaye and L.H. Laby, Tables of Physical and Chemical Constants and Some Mathematical Constants, Longman, New York, 1988.

19. Smithells Metals Reference Book, Eric A. Brandes, Editor, Buttersworth, Toronto, 1983.

20. CRC Handbook of Chemistry and Physics, R.C. West, Editor, CRC Press, Boca Raton Florida, 1988.

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This document describes the results of research carried out at DREA in support of a DMSS tasking to investigate the acoustic properties of composite sonar dome materials. For thin panels (10 mm) at low frequencies (< 10 kHz), the composite materials studied here, as well as the double walled C5 stainless steel sonar window currently used on Canadian naval vessels, exhibited low insertion losses (< 1 dB). For thicker panels or higher frequencies, Spectra Fiber™ is a much better reinforcing fibre than either glass or carbon fibre, in terms of insertion loss. Spectra Fiber composite panels also had much better acoustic properties in the 10 – 60 k Hz range than the C5 stainless steel sonar window (1 dB versus 10 dB at 40 kHz). There was no significant difference in the acoustic properties of panels fabricated with 4 harness satin or 8 harness satin fibre weaves. Panels made from epoxy or cyanate ester resin also had similar insertion losses. The effect of impact damage on the acoustic properties of Spectra and glass reinforced panels was not significant for 10 mm panels at frequencies < 10 kHz. However, there was a significant increase (up to 8 dB) in the insertion loss resulting from impact damage for thicker panels at higher frequencies. The use of elastomeric coatings on composite panels to mitigate impact damage is an approach that may lead to increases in the insertion loss, if air is entrapped between the coating and panel.

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